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HUMAN-INDUCED HAZARDOUS DEBRIS FLOWS IN CARRARA MARBLE BASINS (TUSCANY, ITALY)

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ABSTRACT

In Carrara marble basins, the long and intensive quarrying activities (which began in the first century BC) have produced extensive dump deposits, locally known as *ravaneti*. *Ravaneti* are of such large dimensions and diffusion as to make them a widespread landform of the Apuane Alps (Tuscany). In recent years these quarry dump deposits have been affected by frequent debris flows, more than 50 in 1996/97. This phenomenon is the most significant currently active geomorphological process in this landscape.

The evolution of quarrying techniques produced a variety of sedimentological compositions of *ravaneti*. The debris flows analysed involve only the surface layers where debris is mixed with fine material with a lower permeability (active *ravaneti*) than the coarser underlying debris (older *ravaneti*). The presence of different permeability layers causes a wetting front to move downwards. Source area observations indicate a soil slip movement in the initial phases of the failure. The transformation of landslides into debris flow occurs by means of both soil contractive failure and an increase of granular temperature.

The morphological and sedimentological analyses of depositional lobes resulted in a classification of three types of lobe, based on fabric–morphometry relationships allowing the identification of different flow dynamics: (1) type A lobe (platy form), matrix-supported and well developed fabric with general tendency of *ab* clast plane strikes to lie generally parallel to flow direction as a consequence of laminar flow; (2) type B lobe (elongated form), clast-supported and random fabric as a consequence of both turbulent flow and coarser composition of starting material; (3) type C lobe, intermediate type A–B morphometry, tendency for *ab* clast plane to lie in a semi-circle around the main flow direction determined by the presence of secondary flow lines divergent from it in the stopping phase.

In Carrara marble basins, the anomalous frequency with which debris flows tend to be triggered by medium-intensity rainstorms (about 30 mm h^{-1} rainfall) is due to the recent increases in silt dump produced by modern quarrying techniques. This represents a significant example of debris flows as an environmental problem in major anthromorphized landscapes. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: debris flow; fabric analysis; quarry dump deposit; human-induced hazard; Apuane Alps (Northern Apennines)

INTRODUCTION

Situated in the north west of Tuscany in northern Italy, the Apuane Alps form an elliptical massif whose main axis lies parallel to the Tyrrhenian coast (Figure 1). The Apuane Alps are separated from the Ligurian Sea by the Versilia Plain. The Garfagnana basin to the NE and Lunigiana basin to the NW separate the massif from the main Northern Apennine chain. The highest peaks are in the eastern central part of the massif at Monte Pisanino (1946 m a.s.l.) and Monte Tambura (1890 m a.s.l.) at just 10 km from the coast. The combined location of the Apuane Alps parallel to the Tyrrhenian coast (Ligurian Sea) and the rapid rise of the relief (around 2000 m of elevation in less than 10 km) favours the rapid cooling of damp air masses of Atlantic or Mediterranean origin, inducing intense mountain rainfall ('barrier effect'). Recorded rainfall on the Apuane Alps for the period 1956–1985 in fact shows an average of over 3000 mm a^{-1} with maxima of over 4000 mm a^{-1} just east of the main watershed (Rapetti and Vittorini, 1994). The rain cycle is of sub-

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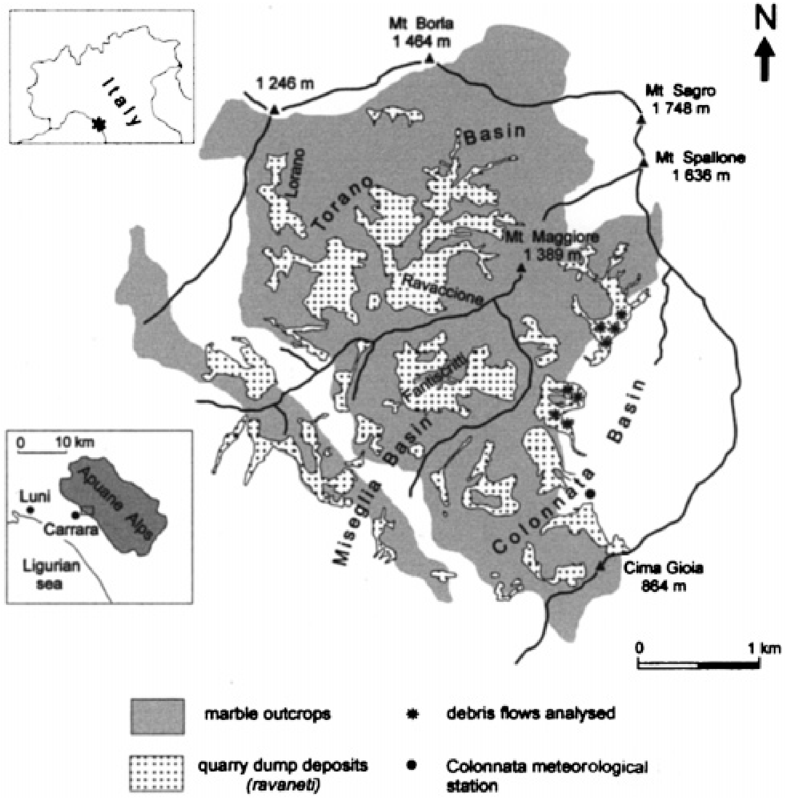


Figure 1. Distribution of marble outcrops and main quarry dump deposits (*ravaneti*) in the Carrara marble basins

mediterranean type, with main maximum in autumn, secondary maximum in winter and minimum in summer.

From a geological point of view the Apuane Alps represent a tectonic window in the Northern Apennine chain from which the succession of units of different tectonic evolution occur (Carmignani *et al.*, 1993, and references therein). The formation yielding the famous Carrara marble (Hettangian) belongs to the Apuane Metamorphic Complex (Paleozoic – Late Oligocene), which was deformed and metamorphosed into greenschist facies beginning in Late Oligocene time. The Oligocene thrusting caused large isoclinal folds which determined the geometry and distribution of the marble beds. In the Carrara zone two vast NNW–SSE trending folds cause the marble to crop out over a large area.

The Carrara marble deposits are morphologically divided into quarrying ‘basins’ which correspond to three valleys on the western (Ligurian Sea) slopes of Monte Sagro (1389 m a.s.l.). Moving westwards these are conventionally known as the Colonnata, Miseglia and Torano basins (Figure 1). The marble basins lie between 300 and 1000 m a.s.l.

As a consequence of quarrying activities that have continued for many centuries, the Carrara marble basins are characterized by extensive dump deposits which form peculiar and widespread landscape features. The accumulations of debris from quarrying operations and *in situ* marble working are known locally as *ravaneti*. They represent a source of environmental hazard in the area, representing a constant threat to quarrying activities and causing hillside instability (*ravaneti* often lie at slopes of over 35°). Debris flow tends to occur whenever the area is subjected to medium-intensity rainstorms.

In the two years of field survey (1996–1997), 52 debris flows were observed. Some of these caused economic damage to the quarrying and interrupted valley roads on several occasions. About 90 per cent of the debris flows examined were of medium and small dimensions, with well defined levees and lobe-form

deposits, which could be classified as hillslope flows (Brunsden, 1979). Some other types of debris flow identified in the Colonnata basin have moved over 600 m and involved considerable quantities of quarry detritus. Debris flows of this type, which cause economic damage and valley road closure, are systematically removed after the event.

Debris flow mobilization models and depositional sedimentological analyses are commonly conducted by laboratory experiments (i.e.van Steijn and Coutard, 1989; Major, 1998), which often do not simulate natural conditions. Laboratory data need to be corroborated by field observations. The recent debris flows in the Carrara marble basins provide new data to corroborate laboratory analyses. This work, besides confirming a recent mobilization model proposed by Iverson *et al.* (1997), stresses the sedimentology and morphology of depositional lobes. A classification based on the fabric–morphology relationship is proposed in order to determine the rheological behaviour in the final stages of flow.

The aim of this work is also to call attention to a major anthropomorphized environmental situation, where human activities can directly induce hazardous hillslope instability. Environmental situations similar to Carrara marble basins are present elsewhere. At Aberfan (Wales), for instance, a debris flow occurred in coal mine dump deposits and flooded part of the village, killing 150 victims (Strahler, 1972). In this context, this work is a contribution for highlighting a general environmental problem from a world famous area, where quarrying continues to this day.

QUARRY DUMP DEPOSITS (RAVANETI)

The temporal evolution of quarrying techniques has produced a variety of sedimentological compositions of *ravaneti*. Knowledge of historical phases of *ravaneti* building is critical to understanding the source area and mechanism of debris flows.

The quarries were first exploited in the Roman period, in the first century BC. The first literary proof of the existence of *ravaneti* from the Roman period is that of the Gallic poet Rutilio Namaziano whose work *De reditu suo*, composed in 417 AD, describes the landscape from the port of Luni (10 km NW from Carrara): *'Dives marmoribus tellus quae luce coloris provocat intactus luxuriosa nives'* (. . . in a marble-covered land which glitters like unblemished snow . . .). Some historians (Dolci, 1985) maintain that these phrases refer to the quarries, whose activity could be seen even at a distance, and proves that there were already deposits of quarry dump at that time.

After the Roman period quarrying was interrupted for a long time, recommencing in the twelfth century, with major exploitation during the Renaissance (i.e. Michelangelo Quarries).

In the eighteenth century explosives were introduced in mining activities, which had until then been carried out almost exclusively by hand. This led to the production of huge volumes of dump material, with a consequent increase in the debris deposit, as well as profound changes in landscape which have affected the area. These today take the form of quarry scars and enormous tips of dump quarry material that cover entire hillsides and valley bottoms (Figure 2).

These highly destructive techniques were abandoned at the end of the 1800s with the introduction of the helicoidal wire cutting method, which allowed a more efficient exploitation of the basins. This system was replaced at the end of the 1970s with the introduction of the faster and easier to handle diamond wire. Although these modern stone-cutting techniques allow more rational exploitation of the marble and reduce tip, the inherent fractures in the rocks mean that only a part of extracted rock can be used commercially. For the main marble varieties produced, the yield is around 50 per cent. These modern extraction techniques produce deposits which contain not only boulders and pebbles of various dimensions, but also a significant percentage of silt, derived from block cutting and squaring.

Actually, a big increase in matrix content in the *ravaneti* derives from reject stone recovery through 'sieving'. This operation is used to separate terrigenous fine material from pure marble pebbles destined for $CaCO_3$ production. This fine material is tipped directly in the *ravaneti*.

A vertical section in the *ravaneti* illustrates a stratified variety of production tippings of different granulometric composition, corresponding to the range of extraction techniques employed over the centuries.

Figure 2. Quarry dump deposits in the Colonnata marble basin

Layers containing abundant matrix can clearly be seen overlying older deposits composed of blocks and coarser debris.

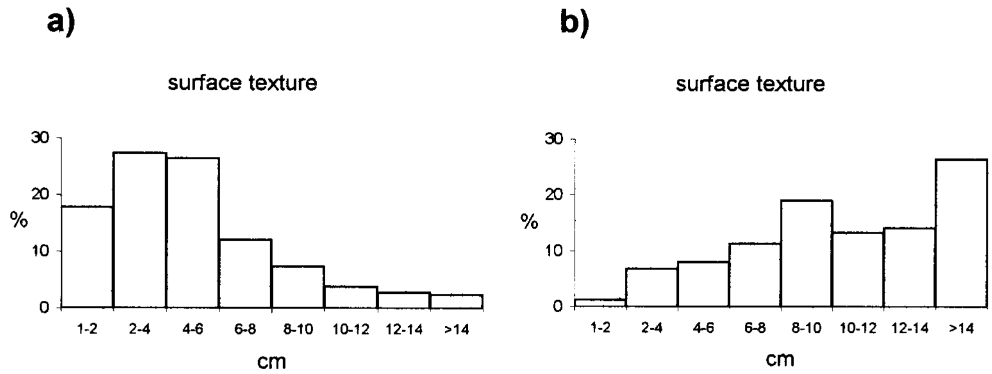
Figure 3 illustrates the surface textures (>1 cm) and matrix composition of 'active' (post-sieving operations) and 'older' (before sieving operations) *ravaneti*. The surface texture was determined by means of the intercept method which consists of measuring the lengths intercepted on clasts along a predefined direction. Atterberg limits of the fine matrix were also indicated. Note that in active *ravaneti* the surface matrix content is more then 40 per cent with isolated patches that overcome 50 per cent while in older ones it is about 30 per cent or less.

DEBRIS FLOW MOBILIZATION

Triggering

Debris flows tend to initiate on steep slopes with heterogeneous debris and high pore pressure. These conditions are fully satisfied in the Carrara quarry dump deposits, where the water content responsible for increased pore pressure can be attributed to rainfall alone. Other common mechanisms, such as rapid snowmelt (Harris and Gustafson, 1993) and stream diversion (Innes, 1983), can be excluded, since the basins lie below 1000 m a.s.1. and surface drainage systems are entirely absent.

The plot in Figure 4 shows rainfall data recorded at the Colonnata station (300 m from the locations of the debris flows studied), representing the lowest rainfall intensity associated with debris flow events. The example quoted refers to a day of relatively intense rainfall (1 May 1996), in which several medium-sized events occur, in addition to a large debris flow which blocked the valley road close to Colonnata village. Total rainfall for the day was 42 mm in about 7 h, with a peak of 33 mm in 1 h during the initial phase of the rainstorm. Consistent rain (45 mm) had fallen in the eight days preceding 1 May, with a peak of 16 mm h^{-1} on 24 April 1996. This suggests that the triggering mechanism for debris flows involves intensity of the initial phase of heavy rainfall, coupled with antecedent rainfall, which form an important factor in lowering the debris saturation threshold. Situations such as that shown in Figure 4 recur frequently in the examined area, particularly in spring and summer, and are always associated with debris flows.



matrix composition		Atterberg limits		
sand	silt	W_L	W_P	IP
53%	47%	20,4 %	15,6 %	4,8

matrix composition		Atterberg limits		
sand	silt	W_L	W_P	IP
68 %	32 %	20,2 %	16 %	4,2

Figure 3. Surface textures (>1 cm), matrix composition and Atterberg limits: (a) 'active' *ravaneto;* (b) 'older' *ravaneto*

Initiation

In the quarry dump deposits, the initiation zone for debris flows generally corresponds to road cuttings or horizontal cuttings in quarry floors. A typical initiation zone feature corresponds to a 1–2 m scarp of semi-circular form on the road plane, which narrows along the slope up to the start of the flow channel, assuming a general V-shaped form. A plane of shallower slope lies at the foot of the scarp. Several tension cracks can be observed around the scarp in the road plane.

The debris flows analysed involve only the surface layers of *ravaneti* where debris is mixed with fine material, with their sliding surface the contact between a fine layer and a coarser older one (see also in Figure 3). Surface layers with abundant matrix have much lower permeability values than coarse underlying debris, therefore the wetting front moves downwards from the surface. In this saturation dynamic, the upper layer may not be entirely saturated and will start to move as soil slip. This mechanism is also supported by the fact that there is little evidence of debris flow in older and coarser (high permeability) quarry deposits.

All these considerations suggest that flow movement starts as a soil slip, and that the moving mass becomes a debris flow after travelling some distance from the source area.

DEBRIS FLOW LOBES

From the survey of the medium-to small-dimension debris flows, it was possible to distinguish three different types of depositional lobes on the basis of their morphology and morphometry. Eight of the most well preserved debris flow in the Colonnata basin were selected for geomorphological and sedimentological analyses. This analysis is based on (a) morphometric indices of debris flow lobes, (b) lobe texture for the >1 cm fraction, and (c) lobe fabric (dip and orientation).

From a morphometric point of view, the different lobe types were distinguished through the dimensions of mean surface slope and lobe front slope, length (in flow direction, L_{max}), width (perpendicular to flow direction, W_{max}) and mean thickness. Lobe texture was determined by means of the intercept method conducted along the two main axes (L_{max} and W_{max}).

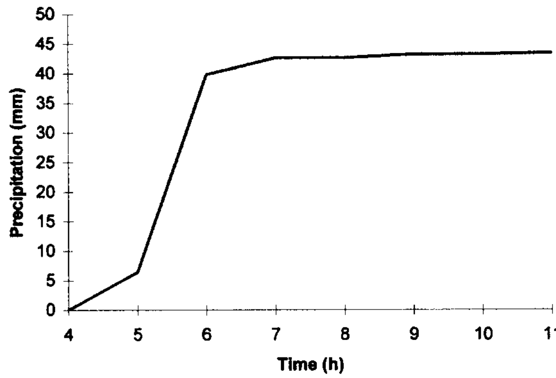


Figure 4. Development in time of rainstorm of 1 May 1996: cumulative curve

The lobe fabric was analysed by measuring orientation and dip of the *ab* planes of the clasts in three significant positions within the lobes. All measurable clasts which fell within a 1 m grid placed in the lobe centre, side edge and front were taken into consideration.

The classification presented below refers to the three lobes considered most typical in describing the classes distinguished, among which a wide range of transitional forms can also be seen.

Type A lobes

Type A lobes were found exclusively on sub-horizontal basal support planes, represented by quarry floors and unused road surfaces located in the medium–lower part of active *ravaneti*.

From maximum dimension values (L_{max}, W_{max}) it was deduced that these deposits are of generally modest volume (less than 10–15 m^3) and range from semi-circular ($L_{max}/W_{max} = 1$) to elliptical ($L_{max}/W_{max} < 1$). Thickness variations along the longitudinal and transverse profile are minor, giving rise to a fairly flat, platy form.

The deposit fabric, generally matrix-supported, is composed of unequal-sized marble clasts with major axis lengths of centimetres to decimetres and the *ab* face greatly flattened, supported by a muddy matrix. The matrix is uniformly distributed on the surface and along the vertical profile of the deposit, showing only slight post-depositional surface runoff. The larger clasts tend to occur more frequently near the lobe front and sides.

The surface texture shows the most commonly represented dimension classes to be 4–6 cm along the major axis and 2–4 cm along the minor axis. This difference can be related to the strong clast orientation with major axis parallel to flow direction.

The most typical and diagnostic feature of type A lobe fabrics is their highly oriented structure. The data for clast *ab* planes show a regular geometric layout (Figure 5). The polar diagram for the central lobe position shows a significant clast grouping of roughly vertical disposition with the *ab* faces almost parallel to the flow direction. The other polar diagram shows details of the front/side zone (due to the small size of the lobe this part could not be distinguished into two separate zones). A gradual transition from directions parallel to the flow (N160E) to perpendicular to flow can be seen. Nearly all the clasts show *ab* downdip towards the lobe centre. The clasts with the *ab* plane perpendicular to flow are those which are found near the lobe front.

There is a general tendency for the clasts to lie with their *ab* planes parallel to the flow, but at the outside edges this changes progressively into a flow-perpendicular orientation at the lobe front. Occasionally random orientations can be explained by clasts whose position is determined by post-depositional tilting and rolling phenomena.

The strong orientation of type A lobe clasts can be attributed to laminar flow, the only phenomenon capable of causing regularly geometrical orientations.

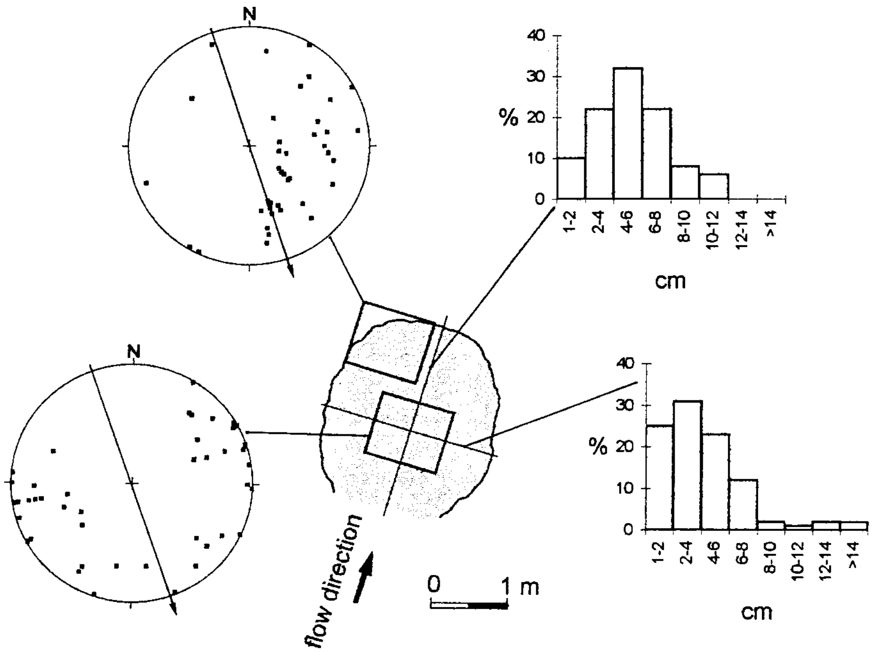


Figure 5. Type A lobe: texture along lobe major and minor axes (intercepts method). Polar diagrams of clast *ab* plane arrangements (Schmidt reticule, lower hemisphere). Arrow indicates flow direction

Type B lobes

Type B lobes extend from lower–middle position to the foot on the tips. In plane projection their patterns are generally elliptical and highly elongated in the slope direction ($L_{max} >> W_{max}$). The debris volumes involved are much greater than for type A lobes (>100 m^3) and their surfaces are strongly convex. In most cases there is a sharp variation in thickness between the lobe centres and their frontal and lateral edges. The lobe shape is generally elongated and bulged with short, steep nose-formed fronts. In contrast to type A lobes, the type B lobes are predominantly clast-supported and locally openwork structured. The minor amount of matrix is mainly concentrated within the body of the deposit.

These lobes are composed of coarse debris with slightly flattened clasts of unequal dimensions. The most frequent dimension classes lie between 4 and 6 cm, with a visible secondary representative class between 8 and 10 cm. Numerous elements exceeding the average (>14 cm) are spread across the entire surface of the debris deposit. Dimensions along the major axis are identical to those along the minor axis, due to the slightly flattened clast forms and the less regular orientation.

The polar diagrams for type B lobes show a generally random layout of the clast *ab* faces (Figure 6). A tendency for the clasts to lie roughly parallel or perpendicular to the slope direction can nonetheless be seen in the central part of the lobe, and the prevalence of upslope-dipping clasts in the front part.

The type B lobes represent moderately imbricated deposits with slight orientation and low packing levels.

Type C lobes

The type C lobes are generally found in association with other types. These deposits generally have several overlying and juxtaposed lobes (flow field aspect). The quarry dump deposits on which they are found are often deeply incised by gullies.

The dimensions and morphometric ratios (L_{max}/W_{max}) vary in value between those typical for type A and type B lobes. Lobe forms are mainly elliptical in plane projection ($L_{max} > W_{max}$) with dips evenly distributed

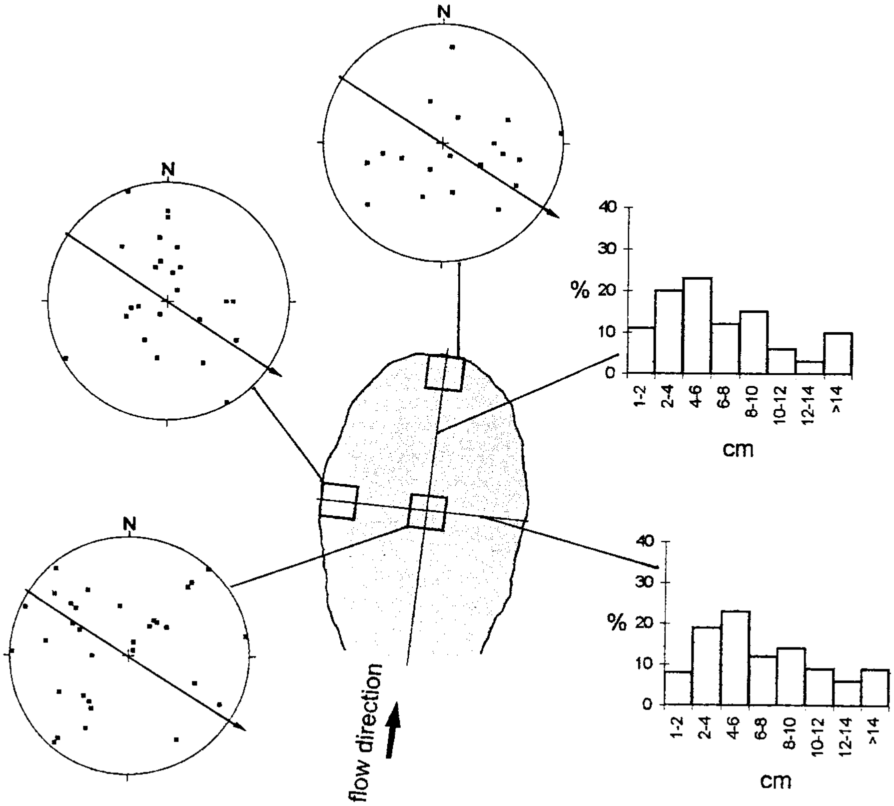


Figure 6. Type B lobe: texture along lobe major and minor axes (intercepts method). Polar diagrams of clast *ab* plane arrangements (Schmidt reticule, lower hemisphere). Arrow indicates flow direction

along the lobe surface. Type C lobes are thus generally elliptical in shape, with slight downslope elongation, thickened in the middle with shallow but distinct fronts.

Clast dimensions fall into the range typical of type A lobes. In the example shown in Figure 7, the most typical dimension class for both directions is 2–4 cm. The deposit has a clast-supported structure. The matrix appears just a few centimetres below the deposit surface in significant quantities and homogeneously distributed.

From the polar diagrams in Figure 7 the clasts can be seen to have good *ab* face orientation, which is nonetheless slightly different from that seen for type A lobes (more clasts are upright and parallel to the flow direction). In the central part of the lobe, clasts with their *ab* faces at 45° to flow direction prevail, while at the frontal portion clast *ab* face alignment tends to be perpendicular to flow direction with upslope dips. The polar diagram of the lobe side portion shows a dispersed 'cloud pattern' indicating a tendency for the clasts to lie approximately parallel to the flow direction, with inward dips.

Here again the general tendency of clast alignment is for their *ab* planes to lie along the lobe contour lines. Unlike type A lobe arrangements, however, this concentric arrangement can also be seen in the centre of the deposit.

Data distinguishing the three types of classified lobes are summarized in Table I.

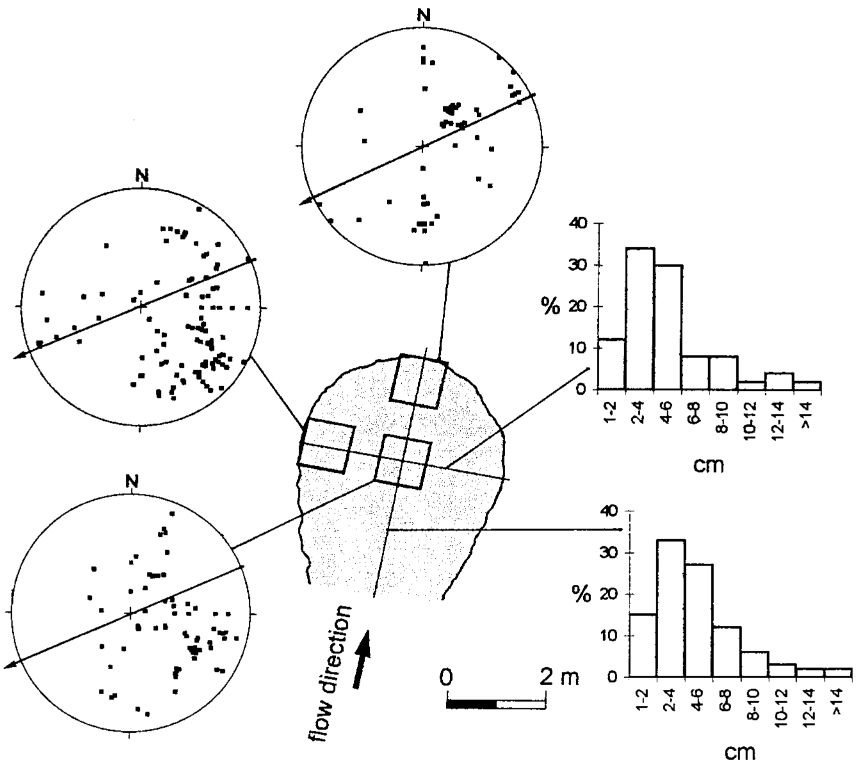


Figure 7. Type C lobe: texture along lobe major and minor axes (intercepts method). Polar diagrams of clast *ab* plane arrangements (Schmidt reticule, lower hemisphere). Arrow indicates flow direction

Table I. Summary of the morphological and sedimentological characteristics of type A, B and C lobes

Lobe type	Morphometry	Volume	Surface texture (class dimension)	Fabric
A	Platy form $L_{max}/W_{max} \leq 1$	$V \leq 10$–$15\ m^3$	Most represented 2–4 and 4–6 cm	Matrix-supported, clast orientated from parallel (lobe centre) to transverse (lobe side) to flow direction
B	Nose form $L_{max} >> W_{max}$	$V > 100\ m^3$	Most represented 4–6, 8–10 and > 14 cm	Clast-supported, open work, random clast orientation
C	Elliptical form $L_{max} > W_{max}$	$20 \leq V \leq 100\ m^3$	Most represented 2–4 cm	Clast-supported, *ab* planes lie in a semi-circle around the flow direction

DISCUSSION AND CONCLUSIONS

This study is the first to analyse debris flows in an area where the activities of humans have had such a strong influence, thus producing an ever-changing landscape. The flows are caused by the abundance of human-produced debris and the occurrence of intense rainfall.

The relationship between rainfall and debris flows observed in the field suggests that limited rainfall is sufficient to cause mobilization. Rainfall records in fact confirm that debris flow activity is possible even in

periods of relatively low rainfall (i.e. Pierson, 1980; Wieczorek, 1987; van Steijn, 1996). A minimum reference value of threshold rainfall level for debris flow initiation was recorded at Colonnata on 1 May 1996. Rainfall was 45 mm in 7 h, 33 mm of which fell in the second hour. The antecedent rainfall of 45 mm in eight days could also have made a significant contribution in deposit saturation and mobilization. Rainfall levels exceeding 100 mm in 1 h (up to 158 mm h^{-1}) have been recorded frequently in northern Tuscany since the beginning of the century (Rapetti and Vittorini, 1991; Rapetti and Rapetti, 1997) and document the potential risk of debris flow initiation in the Carrara marble basins.

In the source areas analysed, the overlaying of two different permeability layers, with a wetting front moving downward, fits with the conditions of a recent experiment carried out by Iverson *et al.* (1997). The field morphological characteristics agree with the initial phases of observations of this experiment. In particular, several tension cracks, as well as retrogressive slumping of multiple soil blocks, were observed. This evidence suggests that the initiation occurs as a surface landslide. The moving mass could not be completely saturated, becoming a debris flow after travelling some distance from the source area. The landslide mass becomes liquefied by means of both soil contractive failure (Ellen and Fleming, 1987) and conversion of translation energy to granular temperature (Iverson *et al.*, 1997). Nevertheless, both mechanisms mentioned here could act simultaneously in transforming a shallow landslide into a debris flow.

The sedimentological analysis of the debris flows is the basis for classifying depositional lobes into three types (A, B and C), and for formulating hypotheses on the final stages of flow rheological behaviour.

Type A lobes show a general tendency for the *ab* plane strikes to lie parallel to the main flow direction, except at the front where they are perpendicular to the flow. This arrangement can be attributed to the ‘freezing’ of the fabric in the laminar flow stage. The central part of the deposit corresponds to the time in which the force of the flow exerted predominant control on clast *ab* plane orientation, and aligned them parallel with the flow. At the lobe front the tractive power of the laminar flow decreases (slowing the flow speed and shallowing the slope), while the effects of internal friction and infra-clastic collision prevail. This causes the clasts to be arranged with their *ab* strikes perpendicular to flow direction, which is a stable, minimum-energy position (Glen *et al.*, 1957).

The general tendency for clast *ab* strikes to lie in a semi-circle around the flow direction, which can clearly be seen in type C lobes, may be explained by the presence of secondary flow lines divergent from the main flow, which are created as soon as the confining action of the levees of the deposit cease (when the flow comes to a stop). This arrangement was also observed by Major (1998) in a large laboratory experiment. The prevalent upslope dips could be induced by variation in vertical velocity, which is less in the lower deposit layers. Certain type C lobes in fact showed concentric ridges attributable to unequal velocity distribution between the inner and surface parts of the debris body.

The relatively random arrangement of type B lobes can be explained either by turbulent flow or by laminar flow where the starting material composition (coarse material with unflattened clasts) inhibits the creation of orientated motion structures.

Although it is generally accepted that deposit structure develops in the final stage of the flow (i.e.Lindsay, 1968; Enos, 1977), the assumption that deposit fabric is orientated by laminar flows and random for turbulent flows is not always recognized (Enos, 1977). Furthermore, Hampton (1972) has shown that debris flows produced by laminar flow also have random fabric lobes.

The sedimentological characteristics of the starting deposit play a fundamental role in determining flow type and the tendency to flow activity. Unlike mountainous areas characterized by widespread coarse debris and little matrix (van Steijn *et al.*, 1988; Blijenberg,1993; Bruschi,1996; Coussot and Meunier, 1996), active *ravaneti* show an abundance of fine material in their uppermost layers, introduced by recent techniques of quarrying, which aids debris saturation.

For this reason, in recent years an increasing number of *ravaneti* have reached critical stability conditions even under non-severe rainfall situations. The debris flows which occur on these quarry dump deposits are potential environmental hazards not only in terms of safety for the quarry, but also through causing economic damage to the continuing quarrying industry.

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